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MODELLING FROM THE PAST: THE LEANING SOUTWEST TOWER OF CAERPHILLY CASTLE 1539-2015

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ABSTRACT:

Caerphilly Castle (1268-70) is the first concentric castle in Britain and the second largest in the UK. The dramatic inclination of its ruinous south west tower has been noted since 1539. Comparing data from historical surveys and a terrestrial laser scan undertaken in 2015, this paper seeks to review evidence for the long-term stability of the tower. Digital documentation and archival research by architects is collated to provide data for structural analysis by engineers. A terrestrial laser scan was used to create a detailed three dimensional finite element model to enable structural analysis of the current shape of the tower made by tetrahedral elements. An automated strategy has been implemented for the transformation of the complex three dimensional point cloud into a three dimensional finite element model. Numerical analysis has been carried out aiming at understanding the main structural weaknesses of the tower in its present condition. Comparisons of four sets of data: 1539, 1830, 1870 and 2015 enabled us to determine change albeit between very different methods of measurement.

1. INTRODUCTION

Figure 1. Caerphilly Castle 2016 (author)

Masonry is a heterogeneous anisotropic material where mortar joints act as a plane of weakness. The failure mechanism of the material includes tensile failure of units and joints, shear failure of joints and compressive failure of the composite. At low levels of stress, masonry behaves as a linear elastic material. Its behaviour becomes increasingly non-linear as the load applied on it increases and cracks develop and propagate. Cracking in masonry structures may be induced by deformation in bending/shear or volumetric changes of the component bricks/stones and mortar arising from natural expansion or shrinkage or temperature change, corrosion, (Cook & Pegam 1993; Bui et al. 2017, Sarhosis et al. 2015; Sarhosis et al. 2016). Experience demonstrates that many masonry constructions have collapsed in the past. Fatigue and strength degradation, accumulated damage due to traffic, wind and temperature loads, soil settlements and the lack of structural understanding of the original construction are some of the factors that contribute to the deterioration as well as the continuous degradation of masonry structures. The loss is even more dominant when damage occurs at historic and cultural structures where damage is most of the times non-reversible. The Cathedral of Mexico City and the Tower of Pisa are two of the most famous examples of historical constructions at risk due to soil settlements (Lourenço 2002).

The need to predict the in-service behaviour and load carrying capacity of historical masonry structures led researchers to develop several numerical methods and computational tools which are characterized by their different levels of complexity (Giamoundo 2014). For a numerical model to adequately represent the behaviour of a real structure, the geometry of the structure as well as the constitutive relationship which characterise the mechanical behaviour of the material must be selected carefully by the modeller. However, it should be considered that cultural heritage structures often show very complex and irregular geometries (i.e. sometimes this is due to distortion and deterioration of the structure).

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The documentation and structural assessment of historical monumental structures is a challenging task for engineers. The use of traditional simplified structural schemes is inadequate due to the complex geometry of such historical structures. Therefore, it is necessary to make use of advanced three dimensional modelling techniques using Computer Aided Design (CAD). However, CAD based modelling is an expensive and complex process and it is often performed manually by the user, which inevitably leads to the introduction of geometric simplifications or interpretations.

Advanced surveying techniques, such as terrestrial laser scanning and close-range photogrammetry, appear very useful tools aiming at meticulously catching the in-situ configuration of historic structures. However, coupling of terrestrial laser scanning with advanced computational methods of analysis for the structural assessment of historic constructions is a challenging issue.

Several scientific contributions attempted to face this problem, see for instance (Arias et al., 2007; Guarnieri et al., 2013; Oreni et al., 2014). Very recently, a novel semi-automatic procedure which transforms 3D point clouds of complex buildings into 3D Finite Elements (FE) models has been conceived in (Castellazzi et al., 2015) and structurally validated in Castellazzi et al., (2017).

In this study, an automated procedure, which directly generates a 3D FE mesh through a rapid processing of the point cloud, is proposed and applied at the case study related to the Caerphilly Castle's south west tower. A preliminary numerical analysis is carried out on the generated FE model and some results are reported and discussed.

2. HISTORIC RECORDS OF THE LEANING SOUTHWEST TOWER OF CAERPHILLY CASTLE

Caerphilly Castle was built in 1268-70 by Gilbert de Clare using pennant stone (Newman, 2002) on a natural gravel bank. In 1539, the Antiquarian, John Leland compared its leaning tower to that of Pisa (Grose, 1783). Between 1928 and 1939, the fourth Marquess of Bute, John Crichton-Stuart commissioned a significant restoration but his father before that, the third Marquis had commissioned a survey by William Frame, an assistant to William Burges in the 1870s (Crook, 1981).

Figure 2. Caerphilly or Sengenneth Castle Pl2 P.Sandby Godfrey 1773 (Grose, 1783)

The date of the specific bombardment which caused the fracture initially is still unknown although we know from Leland's observations that even in 1539 it was understood to have been in the same state "for many ages paft" [sic] (Grose, 1783). The debris of the south-east tower, presumed to have been destroyed at the same time, remain in situ. Although much of the rest of the castle was heavily restored in the nineteenth and early twentieth century, only very minor interventions have been made to the leaning tower, comprising repairs to window heads and minor mortar repairs to vulnerable pointing (Inspector, 2017).

A review of historic observations culminating in Frame's nineteenth century measured survey (Frame, 1870) provides a sequence of benchmarks verifying one another across centuries. From them it is possible to compare notes with geometrical data derived from the laser scan undertaken in 2015 in an effort to establish whether the tower has leant further in that period or not. Although the historic observations are not made with comparable accuracy to that of the laser scanner, they do provide a rare opportunity to contrast impressions made almost 500 years apart.

In 1774 Richard Godfrey, b.1728 and Sparrow depicted Caerphily [sic] or Sengeneth castle in ruinous state – see figure 2. Grose quoted Leland who described in 1539: "Mr. Wood, of Bath, who lay on his back, for several minutes to view this dreadful ruin, its lineal projection, on the outer side, is not less than ten feet and a half". (Grose, 1783). In 1830 the tower is depicted as leaning eleven rather than ten feet: "This bulky fragment of the ruin is between seventy and eighty feet in height, and of a prodigious thickness. It hangs nearly eleven feet out of the perpendicular" (Gastineau et al., 1830). Using the measurements taken from the laser scanner today, it is evident that the greatest lean extends a little over 9ft (2.85m).

Leland's writings were not published until the eighteenth century. However, his comments served to raise the notoriety of the Castle at that time and influenced Camden who stirred rumours of Roman origins in his Britannica: "the tottering wals of Caer-philli Castle, which hath been of so huge a bignesse, and such a wonderfull peece of worke beside, that all men wel nere say it was a garison-fort of the Romans" [sic] (Camden, 1607). Indeed the average thickness of the masonry wall of the tower is 2.91m.

The first comparable benchmark was the determination that the inclination of Caerphilly's south west tower was greater than that of the leaning tower of Pisa, to which Leland had compared it in 478 years ago. Its 10 degree lean recorded through routine monitoring, is regularly referred to today in tourist information as twice that of Pisa which is 5 degrees. "Its height is not by a great deal of much as that of the leaning tower of Pisa, in Italy, it being not above 70 or 80 feet at most; but from the top down almost to the middle, runs a large fiffure…" [sic] (Grose, 1783). The claim can be verified by a comparison with a recent scan at Pisa from DIAPReM research center of the University of Ferrara, ISTI-CNR Pisa and the Department for Architectural Design of the University of Florence. The scan is available courtesy of the CyArK database, overlaying the section confirms that indeed the Caerphilly tower is less than half the height (21.4m shorter) than that at Pisa and whilst the angle of lean is almost twice as acute, the overhang horizontally is 2.85m.

Frame's 1870's section in which the inclination of the tower is set against a vertical plumb-line is held in the Bute Archive at Mount Stuart on the Isle of Bute, Scotland provides the most precise pre-twentieth century survey record available. Its precise

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placement in relation to the plan is frustratingly not noted. However, a comparison between the extent of lean depicted in plan and that determined from the section indicate that is was taken at the largest point of overhang. In Frames' drawing, the lean measures 10.18 degrees from vertical (Frame, 1870). A challenge to our presumption is that the most extreme point taken form the laser scan today results in less dramatic lean of 9.94 degree. Clearly there is scope for the measurements from the drawing to have been distorted, for the precise location of the section on either the scan or the survey not to be the same. That said, it is in fact a relatively minute difference, 65mm horizontally over a vertical length of 15.35m Overlaying the plan and the top view of the laser scan provides another means to compare the measured projection, however the discrepancy of only 65mm is not discernable. It appears reasonable to conclude that the change in lean is negligible over this time period.

Since the care of the castle was handed from the Bute estate first to the ministry of works and then to Cadw, the structural monitoring of the tower through quinquennial condition surveys has included the use of "tell-tale" tags since the 1970's. Reportedly, this has revealed evidence of diurnal movement in the tower in response to changing drying and wetting conditions (Inspector, 2017). This is an issue which could stimulate further potential for monitoring of ground conditions. Indeed, whereas this paper contrasts the earliest records with the latest measurements, it would be desirable to review in more detail the full sequence of records undertaken since the nineteenth century.

3. TERESTIAL LASER SCANNING AND WORKFLOW

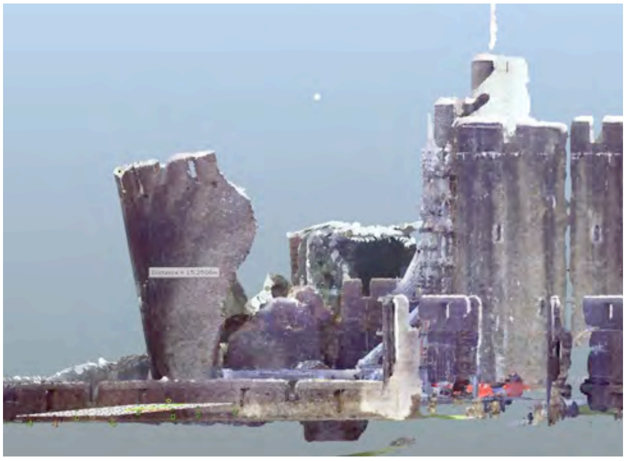

Figure 3. Elevation form laser scan

The laser scan of the south west tower was undertaken by architects during a commission to document the south east tower "tumbles". Using a FARO focus 3D X130 terrestrial laser scanner, a total of 27 scans were made. The inclinometer, altimeter, compass, clear contour and clear sky were also activated and far distance deactivated. The scans were made at a resolution of 1/5 of 28.2 Mpts with 4x quality. The point distance was 7.67mm/10m. A series of scans were taken from points on the ground around the base of the tower, there were challenges in gaining clear lines of sight posed by scaffolded areas and the presence of tourists. A publically accessible first floor walkway through the rear of the tower enabled scans to be taken at high level as well as at ground level. Although the walkway provides a very useful platform, clearly there would be significant additional benefits to using airborne LIDAR to cover all areas including the wall heads. The complexity of the geometry proved challenging in the placement of targets. A total of twelve spherical targets were used in order to locate the scans. No investigations into ground conditions were undertaken. A key challenge on site was the persistence of intermittent rain, although the diffuse light of the sky assisted in preventing overly contrasted RGB data capture.

The scans were registered using FARO Scene software version 5.3. Attempts at automatic registration were largely unsuccessful. Alignment using the spherical targets was limited in success and manual registration was hampered as the curved surfaces of the rough masonry and lack of readily identifiable rectilinear objects made visual demarcation difficult. Eventually after 103 revisions, a point cloud was created. The registration report recorded a mean point error of 6.6mm, a maximum of 15.5mm and minimum overlap of 12.4%. Inclinometer mismatches were up to 0.1279 degrees reflecting the challenge of scanning form two levels.

For the purposes of 2 dimensional comparative examination in CAD, the pointcloud was exported in both .iges format and as .rcp files. Numerous attempts to import the model and generate a 3d mesh in Meshlab failed. However, in Autodesk ReCap, the project was cropped and aligned before being exported in .rcp format to AutoCAD. The 1870 survey drawings were photographed in situ and subsequently rectified in Adobe Photoshop before being examined using overlays in Vectorworks CAD software with 2d .DWG files generated by tracings in Autocad. For the purpose of developing the finite element mesh for structural analysis, the ReCap file was exported as a .rcm file mesh to refine in Autodesk ReMake. Subsequently, the model was exported exported in both .ply and .obj formats for sending to the engineers. It is clear in hindsight that as both Vectorworks and AutoCAD are now able to import pointclouds directly, the potential to draw into such models is becoming significantly more viable without recourse to numerous intermediary steps. In addition, over the two years of working, significant advances in both FARO Scene registration software and the Autodesk suite have served to made many of the travails of this process obsolete.

4. POINT CLOUD PROCESSING AND NUMERICAL ANALYSIS

Aiming at developing a detailed 3D FE model of the south west leaning tower of Caerphilly Castle, a simple processing of the point cloud (Figure 4) has been undertaken. Figure 5 shows the flowchart used for the development of mesh generation which was later used for the structural analysis.

Firstly, preliminary standard operations, such as cloud cleaning, sub-sampling and Triangular Irregular Network (TIN) meshing, carried out starting from the rough point cloud (Figure 4). The obtained TIN mesh is shown in Figure 6 represented by the yellow colour. From Figure 6, such surfaces present several missing parts as the terrestrial laser scanner survey did not reach each surface of the structure. Secondly, in order to generate a watertight surface of the entire structure, a Poisson Surface Reconstruction (PSR) algorithm has been used (Bolitho et al., 2009). Evidently, the PSR algorithm produces an approximation of the surface, specifically on the lacking portions. However, if the missing parts of the surface are limited, as in this case, such

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an approximation can be considered passable for structural purposes. The achieved watertight mesh is represented by means of triangles in Figure 8. Successively, the watertight mesh has been imported into the FE commercial code Abaqus and has been transformed into a FE mesh composed by triangles. Finally, the triangular FE surface mesh is converted into a tetrahedral FE volume mesh (Figure 9) by using a standard subroutine already implemented in the software Abaqus. All the operations carried out for the development of the FE mesh were automatic, with the exception made for the initial tidy up of the rough point cloud.

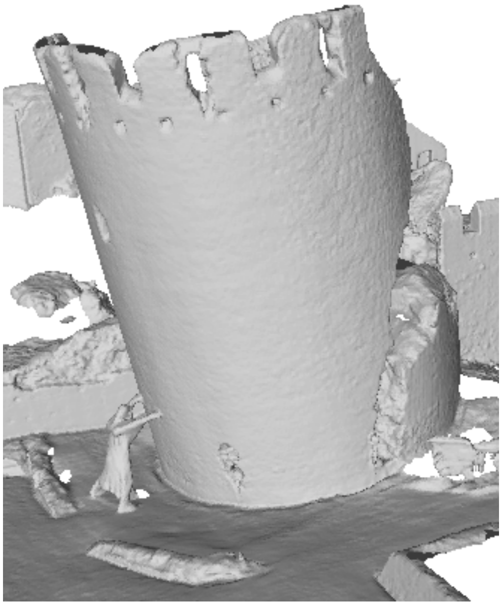

Figure 4. Rough points cloud.

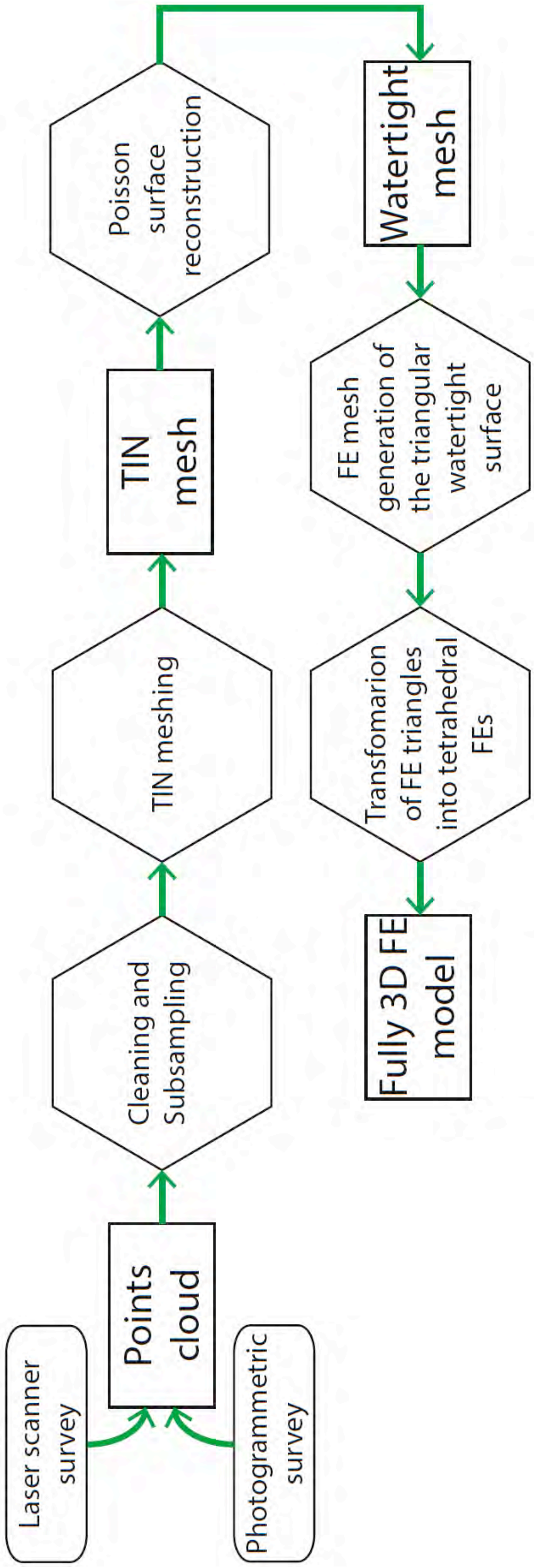

Figure 5. Automated FE mesh generation workflow.

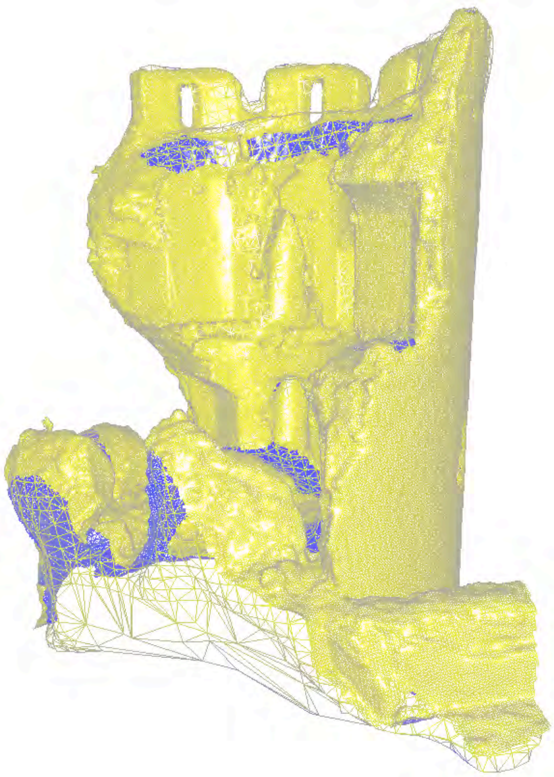

Figure 6. Superimposition of TIN mesh and Poisson reconstruction surface.

A preliminary dead load linear static analysis has been performed on the generated model aiming at investigating the structural condition of the leaning tower. Mechanical properties have been set in agreement with the Italian standards (Technical norms of constructions), choosing a non-regular stone masonry and the lower level of confidence on material characteristics; since no testing was allowed to be performed on the tower. Use of the Italian standards was made since this is the only guidance which provides a complete spectrum of historic materials to be used for the characterisation of structures. In detail, the masonry material properties put into the computational model are: 870 MPa, 0.2 and 1,900 kg/m^3 for Young's modulus, Poisson's ratio and unit weight of the masonry, respectively. Fixed boundary conditions have been employed in the base of the tower.

Figures 7 & 8 show the displacement and tensile principal stress contour plots, respectively. By selecting the worst case scenario of material properties (i.e. this could be due to deterioration of masonry), it was observed that the tower presents substantial displacements under dead load only, which induce the outward rotation of the tower, see Figure 9. Moreover, considerable tensile stress peaks arise, see Figure 10, which suggest the possibility of cracking conditions within the tower. Additionally, Figure 10 (left) highlights sub-horizontal tensile stress peaks which could induce a sub-vertical cracking of the tower's trunk.

Further more advanced structural analysis should be performed, for instance, accounting for the material nonlinearity and the soil-structure interaction aiming at collecting more deepened results.

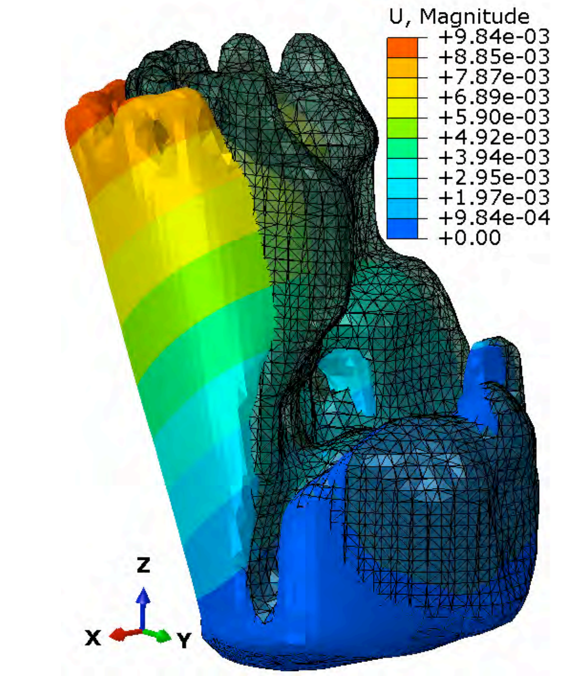

Figure 7. Non-deformed tetrahedral FE volume mesh and dead load linear static analysis: displacement contour plot.

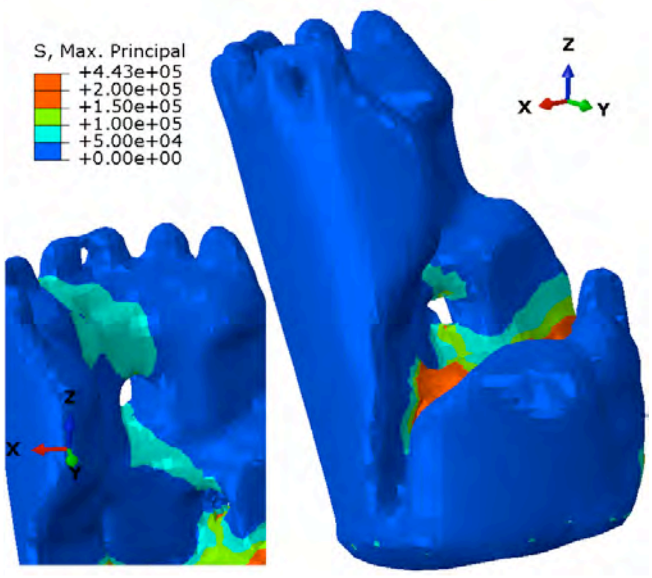

Figure 8. Tensile principal stress contour plot of the tower.

5. CONCLUSIONS

The review of the various oldest historical records appears to reveal that there has been apparently little deformation over this period, as noted above however, there are significant limitations to the accuracy of the available data. The acquisition of further geometrical data with airborne scanning would clearly have been an advantage in improving the quality of the mesh. It would also be rewarding to review the conclusions from the mesh analysis against more recent quinquennial condition reports. Using data from the advanced finite element model developed, we can conclude that in the case of further deterioration of material, the tower could present substantial displacements under dead load which could lead to the outward rotation of the tower. Further work would certainly include a test to review whether the reported 'swings' of the tower can inform the nature of the risk and generate further scope to understand the impact of the ground conditions on the structural stability of the tower. In particular, the collective response of the structure, the foundation, and the geologic media underlying and surrounding the foundation, to seasonal variations and extreme rainfall events will be evaluated.

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